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Spatial prioritization of green infrastructure development in semi-arid cities; a multi-criteria evaluation approach

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Abstract

Green Infrastructures (GI) are one of the main features used for urban drainage system, protecting cities from problems caused by excessive rainfall and runoff. The increasing development of GI in semi-arid cities is driven by its numerous hydrological, social, ecological, and economic benefits. However, a comprehensive framework is needed to identify areas with the highest demand for GI implementation. This study utilizes a Multi-Criteria Evaluation (MCE) approach to identify high-priority sites for GI construction at the city scale, focusing on Tehran Region 5 as a case study. By integrating hydrological, environmental, social, and economic criteria, areas with a high need for GI infrastructure, particularly in addressing runoff generation, were identified. Sensitivity analysis confirmed the robustness of the results, showing consistent prioritization even with varying weights for different layers. The findings highlight the southeast part of Tehran Region 5 as having the highest demand for GI implementation, suggesting targeted interventions in this area. Practical implications of this study lie in providing a framework for managing runoff in semi-arid urban areas and guiding policy decisions towards effective green infrastructure planning. This research contributes to the broader context of sustainable urban development and offers insights into the most effective types of GI for mitigating urban runoff in similar environments.

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Introduction

Urban construction increases impervious areas, resulting in a high rate of runoff generation, overflowing sewer systems, and increasing flood risks. This situation is compounded in semi-arid cities due to intense rainfalls, prolonged droughts, and high evaporation rates in dry seasons (Van Mechelen et al., 2015). Cities in semi-arid climates face water shortages in dry seasons and floods in rainy seasons. During rainy months, torrential rain causes surface runoff and makes seasonal floods (Jamali et al., 2021). Generating runoff moves out of the urban area instead of being collected, reused, or infiltrated. Therefore, the level of groundwater table reduces gradually, jeopardizing urban sustainability (Saeedi & Goodarzi, 2020). So, rapid urbanization in these areas is often at the cost of losing ecological values and generating several environmental, social, and economic problems where cities fail to adopt sustainable urbanization practices

There are many concepts and definitions of sustainability in the context of cities in semi-arid areas. However, they all refer to social, economic, and environmental sustainability (Jiménez Ariza et al., 2019). Within this frame of reference, Green Infrastructure (GI) practices form an opportunity for nature-based runoff management and create additional social (Ureta et al., 2021), environmental (Azari & Tabesh, 2022; Ronchi et al., 2020), and economic (Ossa-Moreno et al., 2017) benefits helping the sustainability of cities. Furthermore, GI practices could mitigate the impacts of climate-change-induced urban floods (Pour et al., 2020), the adverse effects of urbanization on the quality and quantity of runoff in downstream areas (Lodhi & Acharya, 2014), and even urban heat islands (Tian et al., 2021). Therefore, Incorporating GI into the urban fabric might be part of a sustainable solution for cities.

GI is a nature-inspired method for managing stormwater and reducing flood risk. As an innovative stormwater management, GI development focuses on water quality preservation and considers runoff as a resource for sustainable urban development (Saadatpour et al., 2020). In urban contexts, GI comprises micro-scale practices (rain barrels, bio-retention Basins, permeable pavements, green swales, and green roofs) and macro ones (detention ponds and retention ponds). In this research, GI refers to naturally inspired practices, including rain barrels, bio-retention Basins, permeable pavements, green swales, green roofs, detention ponds (dry ponds), and retention ponds. These practices are also known as Low Imapct Development (LID), Water Sensitive Urban Design (WSUD), Sponge City systems, Sustainable Urban Drainage Systems, and Green Storm-water Infrastructure (GSI).

GI has several socio-economic, environmental, and hydrological benefits for cities in semi-arid climatic conditions. In terms of socio-economic factors, GI improves the quality of education (Kevern, 2011), increases aesthetic qualities (Goodarzi et al., 2019; Saeedi & Darabi, 2019), and reduces the operational costs of urban green spaces (Saeedi & Goodarzi, 2020). Environmentally, GI's benefits include increasing water quality (Jia et al., 2012; Urbonas, 2003; York et al., 2015), reducing air pollution (Jayasooriya et al., 2017; Rafael et al., 2018), and protecting biodiversity (Capotorti et al., 2019). Finally, the primary use of GI is runoff control (Grabowski et al., 2022; Kuller, 2016; Saeedi et al., 2022). There is a plethora of hydrological studies that revealed the positive effects of GI on different aspects of runoff quantity and quality. It is worth noting that not all the practices of GI provide all the benefits, and each has its abilities.

An important aspect of GI strategic planning is to select sites with a high need for GI as the financial resources of cities are limited, and GI benefits are highly spatially dependent(Saeedi et al., 2022b). Therefore, a systematic spatial method that identifies sites with high priority for GI construction not only helps decision-makers with wise financial allocation but also maximizes the effects of GI in the context of cities.

Strategic allocation of GI and identifying places with high priorities to control runoff, especially in arid and semi-arid cities, are less addressed. Some of these studies remained serious obstacles in the path of applying the methods for spatial allocation of GI in semi-arid cities. Here is a review of the existing models and frameworks proposed for identifying sites with high need or demand for GI implementation to show the gap of research in this field.

A study conducted by Martin-Mikle et al., (2015), tried to allocate GI practices using Hydrologically Sensitive Areas (HSA). The concept of HAS is for evaluating pollution transport risk, and some aspects of this framework do not comply with GI allocation needs. An important limitation of their framework is that the researchers considered the slope factor as a variable that inversely impacts the spatial prioritization of GI practices. According to the rational model of runoff generation, steep areas produce higher runoff, meaning that the regions with a higher slope have higher priorities for GI allocations. Therefore, contrary to the Martin-Mikle et al., (2015) Model, the slope should be treated as a variable correlated with GI prioritization, and sites with high slopes need to be selected as places with high priorities of GI allocation.

Another study suggests a framework to determine places with high demand and suitability for GI. The criteria selected to specify locations with high needs for GI were categorized into four groups, namely; provisioning (fresh water and food production), regulating (climate regulation, water regulation, water purification, and natural hazard), cultural (aesthetics, educational value, social relations), and refuge habitat (Kuller et al., 2019). Although this study used soil type, slope, hydrology and urban fabric for finding suitable places for GI development, the framework for specifying places in high need of GI does not focus on criteria for prioritizing places as the main goal of GI is controlling runoff at sites where it is produced. Furthermore, their framework is very data-dependent, which makes it hard to use it in the context of cities in developing countries

A recent study conducted by Li et al., (2020) used five groups of layers for planning GI to mitigate urban runoff flooding risk, including storm-water runoff mitigation layers, social flood vulnerable group protection layers, flood-sensitive area road layers, flood-sensitive areas building layers, and environmental justice layers. In this study, to reach the map of the storm-water mitigation layer, the authors used a rational method for calculating the runoff coefficient based on just the map of land use. The runoff coefficient is the outcome of many complex factors like infiltration, antecedent moisture, slope, soil type, and season (Oregon Department of Transportation (ODOT), 2014). However, soil type, slope, and land use are the most important contributing factors in hydrological modeling (Shereif et al., 2014). Therefore, being just dependent on land use for the calculation of runoff generation map is insufficient. Furthermore, the study suggested overlaying the flood risk layer of the city with road layers and sensitive building layers to reach places with high priorities for GI implementation, which is against the definition of GI. GI practices are some nature-inspired techniques that aim to control runoff in places that it generates, not where runoff accumulated. In other words, GI needs to be introduced in the places of runoff generation to maintain contaminants and runoff volume and increase the time of concentration, not the places where flood occurs.

Another recent study by Jamali et al., (2021), suggested a framework for identifying the priority places of GI development in semi-arid cities to reduce storm-water and heat mitigation at the neighborhood scale. The research used a Multi-Criteria Evaluation framework based on GIS analysis and overlaid layers related to population, runoff reduction, and heat mitigation. Although this study used the layer of the population as a proxy for social benefits and heat mitigation as a proxy for environmental benefits, it neglected other indirect benefits of GI, like pollution control, economic benefits, and social support.

According to the literature review, while previous studies have introduced different GIS-based models to calculate each pixel's need or demand for GI development, there are still some important gaps in the proposed frameworks. Therefore, more investigation is needed to develop an integrated, multi-criteria framework for identifying the priority places for GI implementation. Furthermore, there is a lack of framework for prioritizing GI implementation in semi-arid cities. Due to fast runoff generation in semi-arid regions, the prioritization of sites with more potential for generating runoff in semi-arid cities is a crucial factor that is less addressed in previous studies. In addition, while recent studies considered the integrated hydrological benefits of GI practices with other indirect benefits like social and environmental ones, it is important to evaluate the possible economic benefits of integrating GI practices with different land uses as water is an expensive resource in semi-arid cities and need to be taken into consideration. Another important limitation of previous hydraulic-hydrological-based models of GI prioritization is the scale of the study area. So, there is a need for developing GIS-MCE-based models to identify places with high demand for GI implementation.

Therefore, the main objective of the current study is to introduce a physically-based decision-making framework to quantify the need or demand of each pixel for GI in semi-arid urban areas. This framework was developed based on the existing models that used a GIS-MCE model to determine GI demand. However, the authors tried to adapt the proposed framework to the climatic situation of semi-arid cities, cover the gap of previous studies, and integrate the direct and indirect benefits of GI under four main criteria: hydrological, social, environmental, and economic criteria. As the problem of runoff management is more and more serious in semi-arid cities, the proposed framework could be applied to similar urban areas to allocate GI development wisely.

Research methodology

Case study of city scale: Tehran, Region 5

The applicability of the proposed framework was tested through a case study being the city of Tehran as the biggest in Iran and the second-most populous in the Middle East. Tehran is bounded on the north by the Alborz Mountain range and on the south by the deserts of Qom. From the northern margin of this city, seven rivers-valleys flow. These corridors have vital roles as places for energy and wind flows. The land use of Tehran varies from residential, commercial, utility, transport, green space, farmland, and industrial. Due to the high volume of rainfall in rainy seasons, extensive watersheds, and the slope of the city, waterlogging and floods in Tehran occur annually. The flood has become the second serious natural hazard in Tehran. Population increase and the development of impervious surfaces have compounded the problem. Tehran metropolis has more than 8.5 million residents, located at the south foothill of the Alborz Mountains. The city has 22 districts which is shown in Figure 1.

District 5 is a part of Tehran that frequently experiences waterlogging during the rainy season. The central area of the district is densely urbanized, whereas the peripheral zones contain more open spaces and undeveloped land. The district has a slope ranging from approximately 3% to 9%, descending from north to south. Two river valleys flow through the district in a north–south direction. With the exception of large green patches in the northern and eastern parts, most inner-city areas are covered by man-made, impermeable surfaces. The elevation in District 5 varies from 1800 meters in the northwest to 1208 meters above sea level in the southeast, indicating a significant altitudinal gradient. The district also exhibits a diverse distribution of urban land uses (Figure 1). As shown in Figure 1, green and open spaces are unevenly distributed throughout the district. Impermeable surfaces—primarily consisting of residential and commercial buildings, highways, sidewalks, and parking areas—cover a large portion of the area.

Method of identifying places that need GI

The study proposes a multi-criteria evaluation for the allocation of GI in semi-arid cities based on GIS analysis. The framework identifies places with the highest demand for GI placing and increases both direct and indirect benefits of GI in the context of cities located in semi-arid areas.

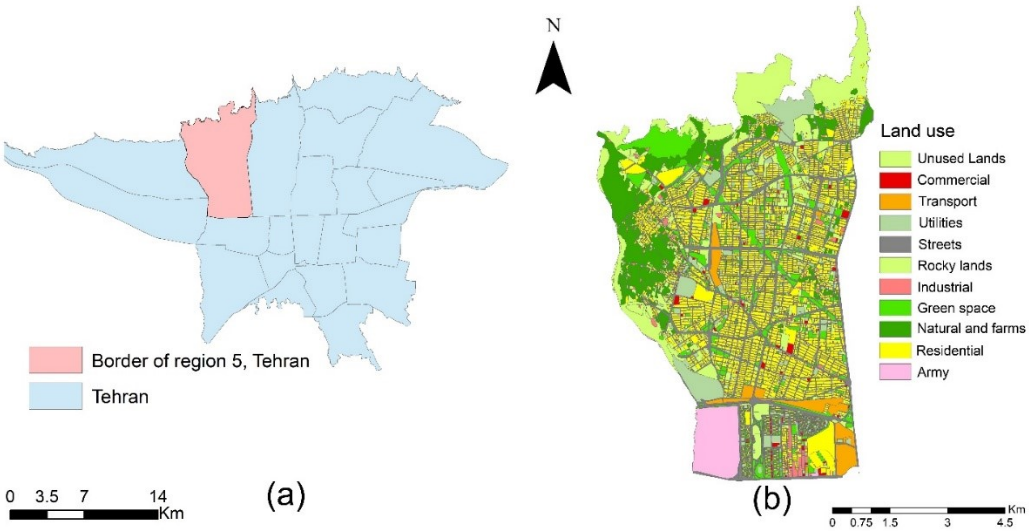

Figure 1. Tehran metropolis, the location of district 5, and its land use

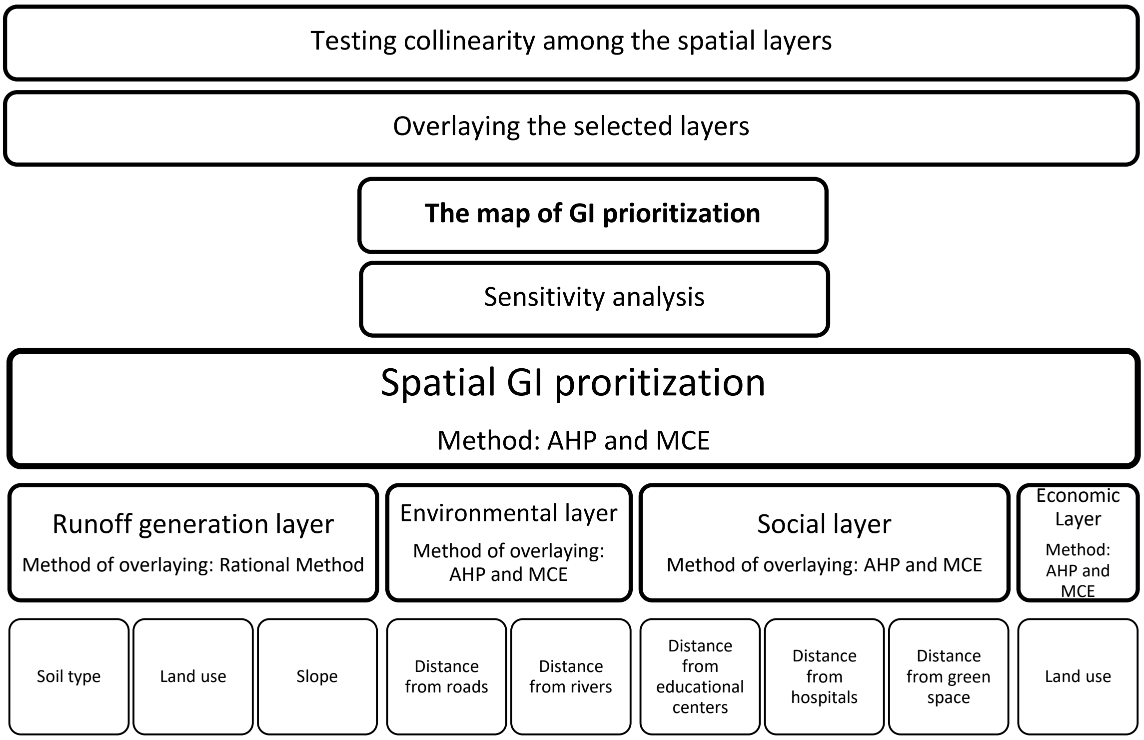

Figure 2. The flowchart of the study for prioritizing GI development

The framework was built based on overlaying four groups of layers: runoff generation, environmental, social, and economic layers, each resulting from several underlying layers. The first layer was used to calculate each pixel's potential runoff generation based on runoff generation process in semi-arid and arid areas. Ecological systems in semi-arid regions are highly fragile and particularly sensitive to stressors such as pollution. Green Infrastructure (GI) practices can enhance ecological stability and are recommended to support the sustainability of arid and semi-arid ecosystems. Accordingly, the second group of spatial layers prioritizes locations for GI implementation based on environmental needs. GI development has been shown to provide numerous benefits to both society and local residents. Therefore, the third group of layers focuses on identifying areas where GI can deliver the greatest social benefits. The fourth group ranks locations based on the potential economic advantages of integrating GI with various urban land uses. Given the critical issue of water scarcity in semi-arid cities, it is essential to utilize unconventional water sources—such as stormwater runoff—to reduce pressure on groundwater extraction. Figure 2 presents the flowchart used to prioritize GI development based on site-specific needs. As shown in the figure, a total of nine physically based layers were used to assess the need for GI at each site, considering hydrological, environmental, social, and economic factors. These layers are described in detail in the following sections.

Runoff generation layer

The structure of cities in semi-arid regions is generally divided into two main components. The first consists of modified and developed areas dominated by impervious surfaces—such as rooftops, streets, sidewalks, and other built environments—which occupy most of the urban space. The second component includes permeable surfaces, typically characterized by exposed soil with sparse and weak vegetation cover. A review of the scientific literature indicates that runoff generation in these two urban components of arid and semi-arid cities can be effectively estimated using the Rational Method (Badiezadeh et al., 2016; Saeedi & Darabi, 2019). Originally proposed in 1850 by Mulyany (Dooge, 1974), the Rational Method remains a reliable approach for estimating runoff, particularly in small catchments with a high percentage of impervious surfaces (Young et al., 2009). Accordingly, the Rational Method was applied in this study to identify areas with high runoff generation potential. The most commonly used form of the Rational Method is presented in Equation 1 (Young et al., 2009).

Equation 1 $$Q_T=CiA$$

Where Q is peak flow for recurrence interval T, C is runoff coefficient, i equals rainfall intensity, and A is watershed area.

When this method is utilized in the context of GIS for spatial planning, A equals the area of each pixel. As the District 5 in Tehran is small area and has just one meteorological station, the amount of rainfall intensity over District 5 was considered the same. Therefore, the runoff coefficient was the only spatially variable factor directly representing the potential of runoff generation in the case study.

Runoff coefficient is the ratio of runoff to rainfall. It is the most important variable of the rational runoff equation. In reality, the runoff coefficient is the outcome of many complex factors like infiltration, antecedent moisture, slope, soil type, land use and season (Oregon Department of Transportation (ODOT), 2014). However, soil type, slope, and land use are the most important determinants in hydrological modeling (Shereif et al., 2014). Therefore, in this research, these three layers were used for calculation of runoff coefficient.

As there is not any proposed runoff coefficient for different land uses of Tehran, we performed a literature review on calculation of coefficient of urban runoff for various areas of the case study based on soil, land use and slope differences. Reviewing the relevant resources resulted in Table 1 for different land uses of Tehran Region 5.

To obtain the map of potential runoff generation, firstly, slope, land use, and soil layers were reclassified to match the runoff coefficient values of Table 1. Then each value of Table 1 was assigned to each relevant polygon. Figures 3a, and 3b show the land use, slope, and soil types of the case study respectively.

Table 1. Runoff coefficients for land uses in Tehran district 5 based on literature review

Land use	Runoff coefficient			Source
	Flat (slope less than 2 percent	Rolling (slope 2-10 percent)	Hilly (slope more than 10 percent)	
Residential	0.70	0.75	0.80	(Oregon Department of Transportation (ODOT), 2014)
Business area	0.80	0.85	0.85	(Oregon Department of Transportation (ODOT), 2014)
Governmental area	0.60	0.60	0.60	(Thompson, 2006)
Industrial	0.60	0.80	0.90	(Oregon Department of Transportation (ODOT), 2014)
Transportation and utility	0.85	0.85	0.85	(Thompson, 2006)
Parks and green space	0.10	0.15	0.25	(Oregon Department of Transportation (ODOT), 2014)
Vacant land (sand and gravel)	0.10	0.20	0.30	(Oregon Department of Transportation (ODOT), 2014)
Asphalt roads	0.85	0.90	0.95	(Thompson, 2006)
Farm land (sand and gravel)	0.25	0.30	0.35	(Oregon Department of Transportation (ODOT), 2014)
Undeveloped rocky lands	0.7	0.7	0.7	

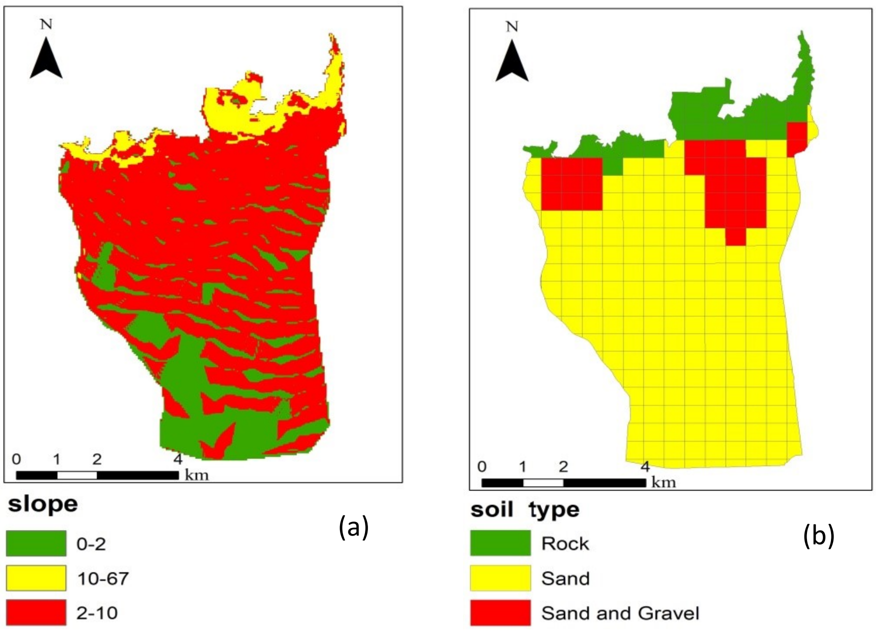

Figure 3. (a) slope and (b) soil types of District 5, Tehran

Environmental layers

Environmental layers examined the relative need of each cell in terms of environmental factors. The environmental criteria selected in this research to enhance the environmental benefits of GI in the context of the city were runoff quality and soil quality.

GI practices aim to control runoff pollution at the source of pollution generation to reduce the risk of contaminant concentration in downstream (Saeedi et al., 2022a). A wealth of research has demonstrated the positive effects of various Green Infrastructure (GI) practices in reducing runoff pollutants such as sediments, heavy metals, nitrogen, and phosphorus. For instance, several studies have reported the effectiveness of bioretention ponds in removing sediments, heavy metals, and chemical contaminants (Ferdinand et al., 2012; Jiang et al., 2015; York et al., 2015). A GI "treatment train" for runoff management consists of a sequence of process-based components, including on-site interception, on-site treatment, flow attenuation through routing, and regional storage or treatment (Shoemaker et al., 2009). Figure 4 illustrates a complete GI chain for runoff control, where each component represents a specific GI type. For example, a rain barrel can serve as an on-site interception measure, while an infiltration trench can function as an on-site treatment unit. By strategically employing GI types suitable for on-site treatment or storage, it is possible to capture pollutants at their source (i.e., upstream of drainage outlets), prevent their movement downstream, and reduce their spread across the watershed. In this study, proximity to major rivers and canals was used as a proxy for runoff pollution source control. Areas located closer to rivers and canals were assigned a lower priority for GI implementation, whereas locations farther from these water bodies were given higher priority (Figure 5). Although several GI types are suitable for flow attenuation, their application was not recommended in this case study. Tehran lacks a separate wastewater conveyance system; most of its greywater is combined with stormwater and flows downstream for eventual treatment or storage. To improve the effectiveness of GI chains in such an urban context, it is first necessary to separate the stormwater conveyance system from the wastewater network. Once separation is achieved, areas with a high demand for treatment or storage should be identified. Roads and highways are major sources of urban soil contamination, introducing pollutants such as heavy metals (e.g., cadmium, zinc, copper, and lead), oils, debris, and solid waste (Kaykhosravi et al., 2019). Moreover, land uses near highways—such as parking lots and vehicle repair shops—are often associated with further soil pollution. Studies have shown that GI installations, particularly bioretention basins, are highly effective at retaining metals and capturing debris (Debo & Reese, 2002; Liu et al., 2017; Water & Commission, 2013). Therefore, the distance of each pixel from main roads and highways was used as a proxy to address soil contamination risks. Areas closer to major roads and highways were assigned a higher priority for GI allocation (Figure 5).

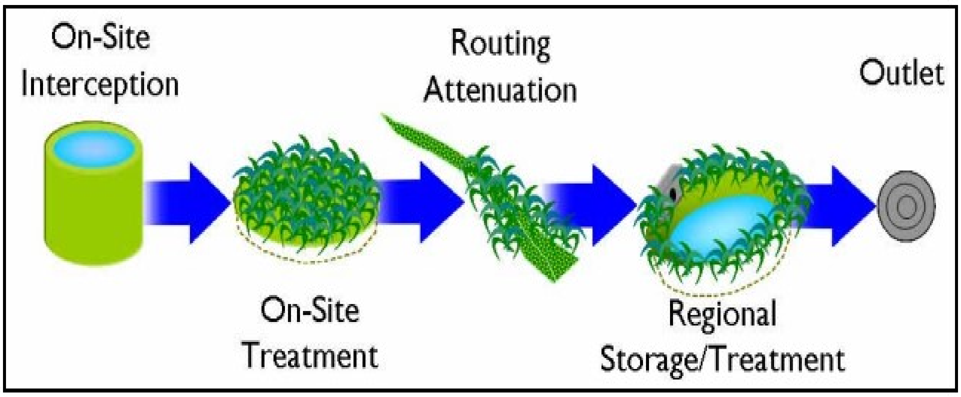

Figure 4. A schematic of complete GI treatment for runoff control (Shoemaker et al., 2009)

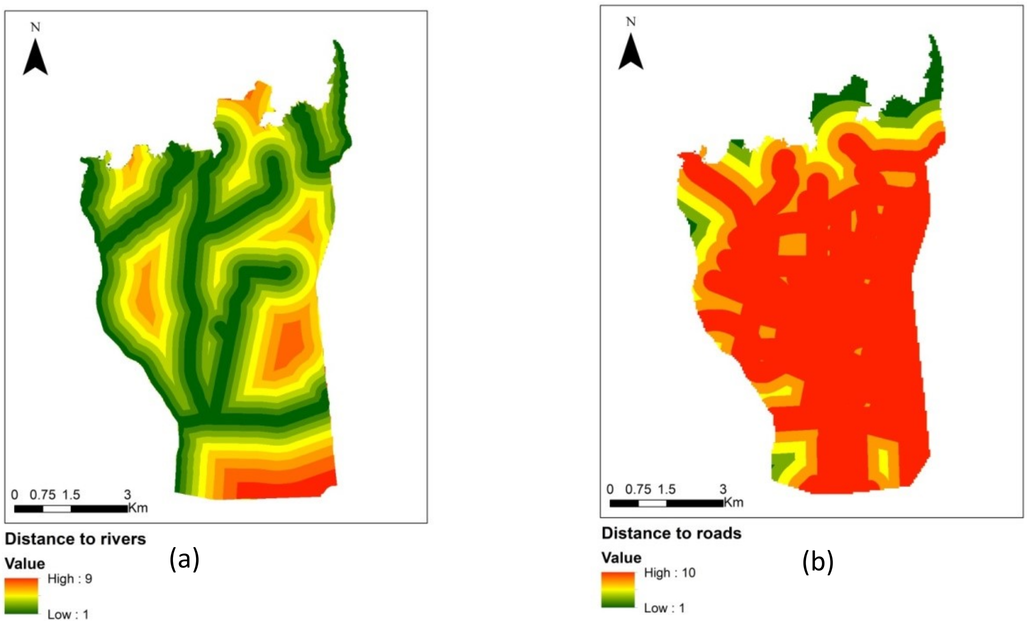

Figure 5. Environmental variables: (a) distance from rivers and (b) distance from roads

Social layers

Social layers quantify the GI demand of each spatial unit in terms of potential social benefits. GI practices can offer a wide range of social advantages, including improving access to green spaces, enhancing physical and mental well-being, reducing environmental injustice, and supporting educational objectives. Accordingly, the social layer set aims to maximize these benefits through four key indicators: distance from urban parks and green spaces, distance from medical centers and hospitals, and distance from educational institutions (Figure 6). Every city has a network of parks and green spaces intended for daily public use. However, cities in arid and semi-arid regions often have less green space compared to those in temperate climates, largely due to high irrigation costs and limited water availability. Since the presence of greenery directly affects both runoff management and social well-being (Li et al., 2020), prioritizing areas with limited green space is crucial for equitable GI allocation. Therefore, the “distance from parks” layer assigns higher priority to areas farther from existing parks and landscapes, aiming to improve access to green space in underserved neighborhoods and promote a more balanced spatial distribution of GI benefits across the city. Exposure to natural environments and greenery has been widely recognized for its restorative physical and psychological effects (Kaplan & Peterson, 1993; Stigsdotter & Grahn, 2002). Studies have shown that patients recover more quickly in hospitals with views of green spaces (Andrade & Devlin, 2015). This concept is encapsulated in the "healing landscape" approach, which highlights the therapeutic effects of viewing natural features such as vegetation, water, and flowers (Lau et al., 2014; Saeedi et al., 2015; C. W. Thompson, 2011). Based on this understanding, areas in close proximity to medical centers and hospitals were given higher priority for GI implementation to enhance the therapeutic potential of these environments. The final social layer considers the distance from educational centers. Locations near schools and universities were prioritized to leverage the indirect educational and developmental benefits of GI for students. Research has demonstrated that GI can enhance students' cognitive performance, social behavior, and academic outcomes. For instance, Scott et al. (2018) found that preschool children exhibited greater independence and improved social skills in neighborhoods with permeable surfaces. Similarly, green space has been linked to better cognitive restoration, reduced stress, and improved quality of life among students (Guo et al., 2020; Hipp et al., 2016; Lu & Fu, 2019). Frequent visits to green spaces have also been shown to alleviate perceived stress in university students (Holt et al., 2019).

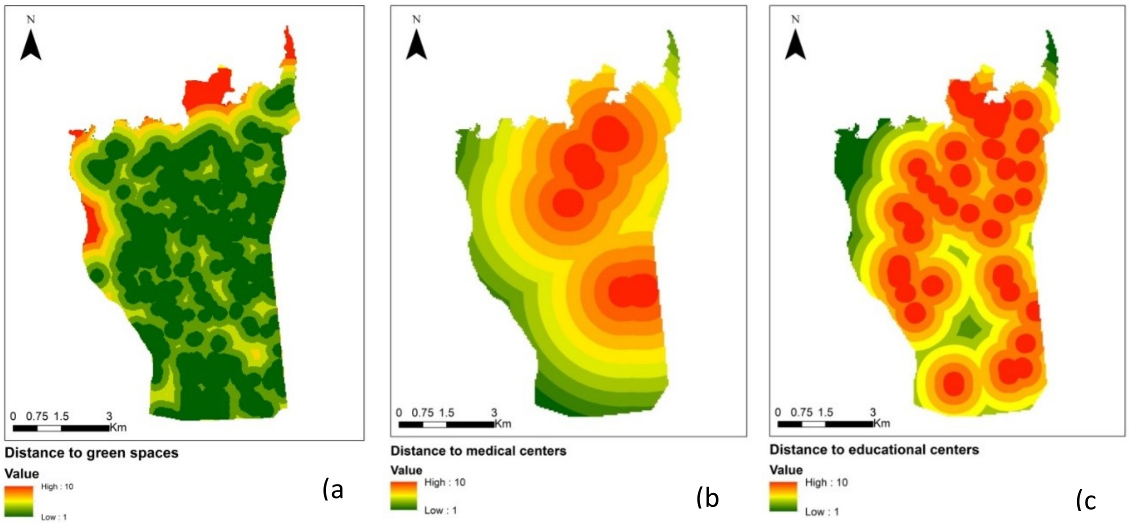

Figure 6. Social layers for GI prioritization for Tehran District 5; (a) distance from green spaces, (b) distance from medical centers, .and (c) distance from educational centers.

Economic layer

Water scarcity in semi-arid countries like Iran is getting so severe that more than 500 cities have run into the harsh risk of potable water shortage, one of which is Tehran (Zehtabian et al., 2010). An important reason for this phenomenon is neglecting runoff and treating it as a waste that should be discarded (Walsh et al., 2014). Cities located in arid and semi-arid regions face the problem of water shortage in dry months and waterlogging or floods in rainy seasons (Zhang & Hu, 2014). During rainy seasons, torrential rain makes massive runoff flow the streets and move out of the city instead of being collected or conveyed to the groundwater. On the contrary, the city is dependent on groundwater to meet the citizens' needs and irrigate the existing green spaces. Some Iranian cities even buy irrigation water with trucks to irrigate urban landscapes (Saeedi & Darabi, 2019). Therefore, this approach creates insurmountable pressure on groundwater and increases the cost of landscape maintenance for municipalities.

GI in semi-arid cities has several financial benefits; an important quantifiable benefits is reusing collected rainwater. GI practices have the ability to be integrated with some urban land use that could consume water for irrigation and non-potable purposes. For example, Saeedi & Goodarzi, (2020) showed that implementing GI practices in Green spaces reduces the cost of irrigation and leads to sustainable landscape design. Furthermore, residential and commercial sites could reuse rainwater for domestic uses like washing, toilets, laundries, and small-scale irrigation (Zhang et al., 2012). GI practices also can be integrated with industrial or transportation areas (Yannopoulos et al., 2019). For example, the rainwater harvesting system of Frankfurt Airport restores one million cubic meters, and the collected rainwater is used chiefly for toilet flushing, cleaning the air condition systems of the airport, and landscape watering (Rao & Giridhar, 2014). Therefore, the economic layer assigns priority to the land uses that could be integrated with GI and enjoy the financial benefits of GI.

Based on a literature review conducted to assess the economic value of GI practices across various land uses, the potential of each land use type for GI integration was identified. Table 2 presents the prioritized land uses and their corresponding scores in the economic layer of the analysis. The highest score was assigned to vacant lands, recognizing their potential for future development and the ease with which GI can be incorporated from the outset. Green spaces and farmlands were also given high priority (score of 9), as they can be effectively integrated with GI systems to utilize collected runoff for irrigation, thereby generating direct economic benefits. Residential, commercial, and industrial areas were also evaluated for their potential to support GI practices such as rain gardens, rainwater harvesting systems, green roofs, and infiltration trenches. Residential areas received a score of 8 due to their dual structure—yards and rooftops—both of which provide suitable sites for GI installation, enhancing water reuse and cost savings. Commercial land in Tehran typically consists of small street-front shops with limited space and structural suitability for GI integration; therefore, this category received a lower score of 6. Industrial zones, although limited in Tehran and often characterized by aging infrastructure, still offer some GI potential and were assigned a score of 7. Finally, transportation and utility areas were given the lowest priority. Due to high levels of pollution and contamination, the runoff collected in these areas is not suitable for reuse, limiting the economic feasibility of GI implementation.

Table 2. The priorities given to different urban land uses for GI allocation

Land use	Priority from 1 to 10
Green spaces	9
Vacant lands	10
Farm lands	9
Residential	8
Commercial	6
Industrial	7
Transport and utilities	6

Testing collinearity

To avoid collinearity among layers with continuous values, correlations were calculated using Principal Component Analysis (PCA) module in TerrSet software. The maximum correlation was 0.7 which is lower than 0.8 indicating reasonable independence of the selected layers.

Overlaying layers

Finally, all the layers were weighted using the Weighted Sum command in ArcMap. Under the supervision of senior professors in water management, land use planning, and landscape architecture, An Analytic Hierarchy Process (AHP) method was used to derive weights for environmental, social, economic, and runoff generation criteria. The overall inconsistency was 0.02 indicating the validity of the weights. The weights are shown in Table 3.

In the next step, the standardized layers were overlaid based on the weight assigned using the Weighted Sum command and the ArcMap. Equation 2 shows the method for overlaying the selected layers (Mehri & Salmanmahiny, 2017).

Equation 2: $S= \sum_{n}^{i} WiXiCi$ ..

where S equals GI need, Wi is the weight of the layer, Xi represents the standardized layer and Ci is Boolean layer showing excluded areas.

Finally, all the layers were weighted and overlaid using the **Weighted Sum** tool in ArcMap. To determine the weights for the environmental, social, economic, and runoff generation criteria, the Analytic Hierarchy Process (AHP) was applied under the guidance of senior experts in water management, land use planning, and landscape architecture. The overall inconsistency ratio was calculated to be 0.02, indicating a high level of consistency and reliability in the assigned weights. The weights of the selected layers, along with the standardization methods and their respective values, are presented in Table 3.

Table 3. The weights, standardization methods, and values of the layers used for identifying GI demands

Layer	Weight	Standardization method	Value
Runoff generation potential	0.4145	Values of Table 1 ×10	1-10
Economic layer	0.1861	Table 2	1-10
Distance from main rivers and canals	0.1391	Linear–decreasing	1-10
Distance from main roads	0.1391	Linear-decreasing	1-10
Distance from hospitals	0.0404	Linear-decreasing	1-10
Distance from educational centers	0.0404	Linear-decreasing	1-10
Distance from green spaces	0.0404	Linear-increasing	1-10

Sensitivity analysis

Uncertainty in the weighting of criteria may arise due to subjectivity or limited knowledge of the respondents. To address this issue, a sensitivity analysis was conducted to assess the impact of potential uncertainties on the spatial prioritization results for GI development. The **One-at-a-Time (OAT)** method was employed for this purpose. In the OAT approach, only one parameter (i.e., weight) is modified at a time while keeping all others constant, allowing for the evaluation of that parameter's individual influence on the model output. To implement the sensitivity analysis, 10% was either added to or subtracted from the original weight of each criterion layer. The added or subtracted amount was proportionally distributed among the remaining criteria to ensure the total sum of weights remained equal to one. As a result, two adjusted weighting scenarios were created for each layer. Since seven layers were involved in the GI prioritization, a total of 15 weighting scenarios were produced—14 adjusted scenarios and one original baseline scenario. Each of the 14 modified weight sets was used to generate a new priority map by repeating the overlay process through the **Weighted Sum** tool in ArcGIS. Subsequently, the differences between each of the 14 maps and the original GI priority map were assessed using the **Crosstab** function and **Kappa coefficient** in **TerrSet** software.

Results

Runoff generation potential

To evaluate the runoff generation potential in the study area, slope, soil type, and land use layers were overlaid, and each polygon was weighted based on the criteria provided in Table 1. The resulting map was color-coded to illustrate the gradient of runoff generation, ranging from the lowest to the highest potential (Figure 7). As shown in Figure 7(a), the runoff generation values in Region 5 of Tehran range from 1 to 9.5. The overall slope increases from south to north. Due to the uniformity of soil types in the study area, land use and slope emerged as the primary contributing factors to runoff generation. Accordingly, areas with high imperviousness and steep slopes exhibit the greatest potential for runoff. Most parts of Region 5 consist of impervious surfaces and therefore have high runoff coefficients. In particular, the southeastern portion of Region 5, characterized by compact impervious land uses, generates more runoff compared to the western and northern sections. In contrast, the western and northern areas contain natural patches and permeable surfaces, resulting in lower runoff production. To highlight locations with the highest runoff generation potential, areas with values greater than 8.47 were identified—this threshold being equal to the mean runoff value (5.67) plus one standard deviation (2.80). Figure 7(b) presents these high-priority locations, which are primarily roads and areas in the southeastern part of the district. In contrast, the northern and western portions generate significantly less runoff. The runoff potential map derived from the GIS analysis provides a valuable tool for identifying areas that contribute most to flooding and waterlogging. In

Region 5 of Tehran, these high-impact zones are predominantly located in the southwest and are associated with transportation-related land uses. Prioritizing these locations for the implementation of green infrastructure (GI) practices can improve the overall effectiveness of stormwater management while enabling more efficient allocation of resources.

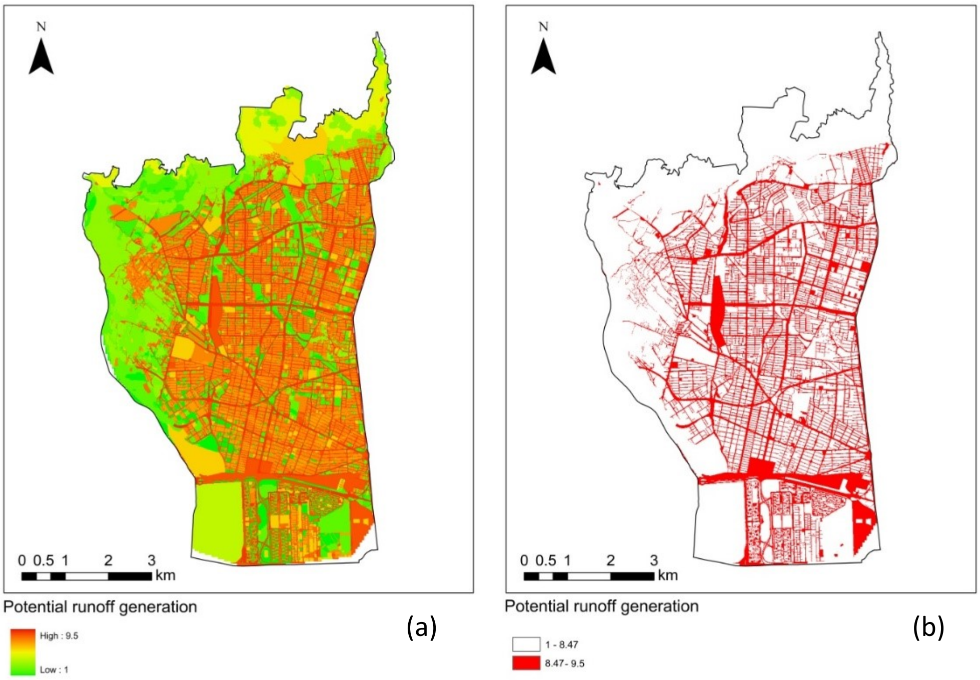

Figure 7. (a) Runoff generation map, (b) places with the highest potential for runoff generation

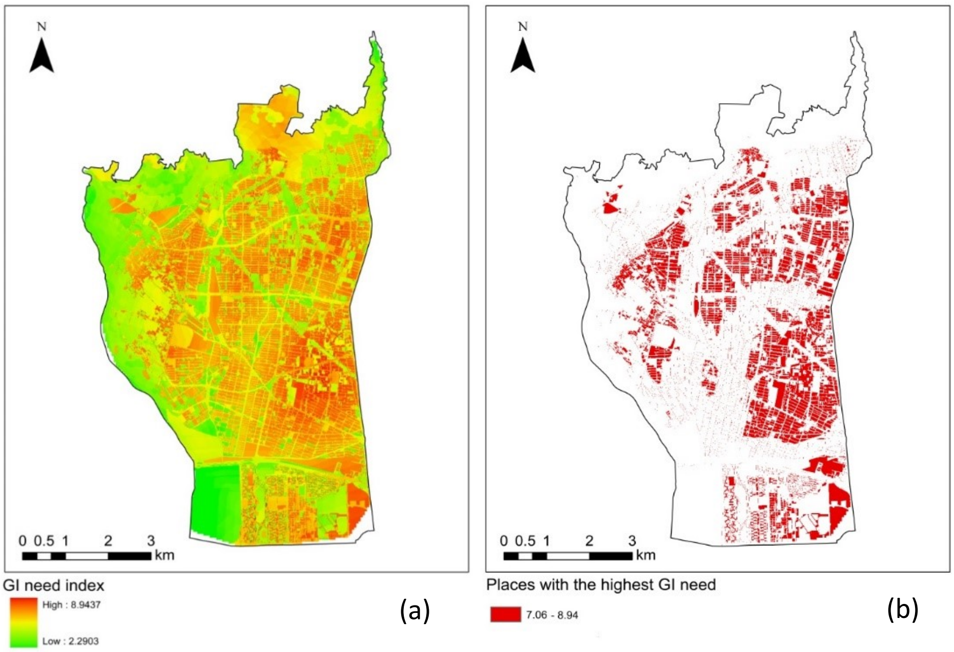

Figure 8. (a) The map of GI prioritization, (b) places in need of GI

Identifying places with high GI need

Figure 8 presents the final GI priority map, with values ranging from 2.3 to 8.94, a mean of 6.01, and a standard deviation of 1.05. The figure also highlights areas with values exceeding the threshold of 7.06 (i.e., mean + standard deviation). A comparison between the runoff generation map (Figure 7) and the final GI priority map (Figure 8) reveals the influence of environmental, social, and economic criteria. Some areas were either excluded or included in the GI priority map based on the presence or absence of these additional considerations. Certain exceptions were made in the GI needs map for District 5. Areas with slopes greater than 45 degrees were omitted, as this is generally the maximum slope considered stable for land development. Additionally, military zones were excluded due to security restrictions.

However, private lands (such as yards and rooftops) and public areas (such as streets and walkways) were not excluded from the GI demand map. This decision was based on the importance of implementing onsite control measures—small-scale practices such as green roofs, porous pavements, bioretention basins, and rain barrels—that can be installed on private properties and play a significant role in reducing runoff volumes. These measures are also essential components of sustainable urban drainage systems.

Sensitivity analysis

Table 4 presents 14 different weighting scenarios used to conduct the sensitivity analysis. Using the **Weighted Sum** tool in ArcGIS, 14 new GI prioritization maps were generated based on these scenarios. Each of these maps was reclassified into five categories, consistent with the classification in the main GI prioritization map (Figure 8). Subsequently, the **Crosstab** tool in TerrSet was used to compare each of the 14 new maps with the original GI priority map, calculating the levels of agreement, disagreement, and the Kappa coefficient (as shown in Table 5).

As indicated in Table 5, the level of disagreement between each of the 14 weighting scenarios and the final GI prioritization map (Figure 8) is less than 1%, and all Kappa coefficients exceed 0.9. These results demonstrate a high level of agreement across the scenarios, confirming the robustness of the prioritization model. Additionally, the highest levels of disagreement were observed among the **very low**, **low**, and **medium** priority classes.

Table 4. The weight of layers designed to perform sensitivity analysis

		Weight scenarios considered														
	Layers	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Economic	0.1861	0.1675	0.1868	0.1868	0.1868	0.1884	0.1884	0.1930	0.2047	0.1854	0.1854	0.1854	0.1838	0.1838	0.1792
2	Distance from educational areas	0.0404	0.0435	0.0364	0.0411	0.0411	0.0427	0.0427	0.0473	0.0373	0.0444	0.0397	0.0397	0.0381	0.0381	0.0335
3	Distance from green spaces	0.0404	0.0435	0.0411	0.0364	0.0411	0.0427	0.0427	0.0473	0.0373	0.0397	0.0444	0.0397	0.0381	0.0381	0.0335
4	Distance from medical centers	0.0404	0.0435	0.0411	0.0411	0.0364	0.0427	0.0427	0.0473	0.0373	0.0397	0.0397	0.0444	0.0381	0.0381	0.0335
5	Distance from rivers	0.1391	0.1422	0.1398	0.1398	0.1398	0.1252	0.1414	0.1460	0.1360	0.1384	0.1384	0.1384	0.1530	0.1368	0.1322
6	Distance from main roads	0.1391	0.1422	0.1398	0.1398	0.1398	0.1414	0.1252	0.1460	0.1360	0.1384	0.1384	0.1384	0.1368	0.1530	0.1322
7	Runoff generation potential	0.4145	0.4176	0.4152	0.4152	0.4152	0.4168	0.4168	0.3731	0.4114	0.4138	0.4138	0.4138	0.4122	0.4122	0.4560
	Sum	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

Table 5. Changed area, percentage of changes, highest change between classifications and Kappa coefficient of the sensitivity analysis

Scenario	Total percent of changed area (%)	Changed area (m2)	Kappa coefficient	Highest change between classifications
2	0.4	215390	0.9516	Low to very low
3	0.1	45380	0.9926	Low to very low
4	0.2	135140	0.9926	Medium to low
5	0.1	32560	0.9951	Low to medium
6	0.4	227250	0.966	Very high to high
7	0.5	288710	0.9567	High to medium
8	1.0	541440	0.9187	Medium to high
9	0.6	346290	0.9481	High to medium
10	0.1	68700	0.9897	Low to very low
11	0.2	96560	0.9855	Medium to high
12	0.1	48430	0.9927	Low to very low
13	0.4	195470	0.9707	Very high to high
14	0.5	293680	0.956	Very high to high
15	1.0	537850	0.9197	Very high to high

Discussion

Using GIS and Multi-Criteria Evaluation (MCE), this study aimed to generate a priority map for green infrastructure (GI) development in District 5 of Tehran to address urban surface runoff, flood risk, environmental pollution, and provide socio-economic benefits. By integrating hydrological, environmental, social, and economic criteria, areas with the highest need for GI—particularly those contributing significantly to runoff generation—were identified. The findings highlight the southeastern part of Region 5 as the area with the greatest demand for GI interventions. The implementation of nature-based solutions to manage runoff at its source is a key strategy for flood control in Tehran (Jamali et al., 2021; Mani et al., 2019). However, as depicted in Figure 8, the current distribution of green spaces across the city does not align with the areas of highest GI need. For instance, the northwest of the district contains more green spaces, despite having relatively low demand for GI. In contrast, the densely developed neighborhoods in the southeast—where the need is greatest—lack sufficient green space. Given the high cost of land in these compact areas, converting residential land to public green spaces is not feasible. Therefore, site-scale GI practices compatible with dense urban environments, such as porous pavements, green roofs, rainwater harvesting systems, and infiltration trenches, are recommended. A relevant study by Saeedi et al. (2022b) on selecting suitable GI types and treatment trains for Tehran could inform the next phase of GI planning.

Natural environments in semi-arid regions are highly sensitive to disturbances (Yang & Wang, 2017). In urban settings, this sensitivity is exacerbated by multiple stressors, notably the accumulation and downstream transport of pollutants washed from impervious surfaces (Meerow et al., 2021). This issue is prevalent in the study area, where pollutants from urban runoff are annually carried downstream (Mani et al., 2019). While downstream treatment is a cost-effective method for improving runoff quality, it is insufficient as a standalone strategy. As illustrated in Figure 4, upstream GI implementation is crucial to prevent pollutant transport. This study provides a spatial framework to identify priority locations for GI to reduce such upstream-to-downstream transfers. Moreover, the runoff-priority layer developed here can be integrated into future studies using hydrologic-hydraulic modeling to optimize runoff quality management.

Although many studies have examined the socio-economic benefits of GI in semi-arid regions (Choi et al., 2021; Jiang et al., 2015; Meerow et al., 2021), few have incorporated these criteria into the spatial allocation of GI. This study proposes a flexible framework that allows for the inclusion of additional economic and social layers in future research—such as property value impacts, neighborhood satisfaction, and psychological well-being (e.g., stress reduction). This adaptability enhances the model's relevance to local conditions and emerging urban priorities. The GI demand map for Tehran Region 5 simplifies a complex, multi-criteria decision-making problem. It visualizes the primary sources of runoff generation alongside socio-economic and environmental priorities. This visualization aids in understanding the interplay between flood risks and development needs, offering a valuable reference for planners and policymakers. The flexible framework also allows for selective prioritization of social, economic, or environmental factors and accommodates financial and resource constraints. Decision-makers can export top-ranked GI-priority areas for strategic implementation, enabling more efficient resource allocation and greater overall benefit. The methodology developed in this study is adaptable and can be scaled for use in other parts of Tehran or other semi-arid cities. It provides a pixel-based assessment of GI need, which can inform a strategic urban GI plan that addresses typology, regulations, site suitability, and runoff control. Ultimately, this study contributes to informed spatial planning and prioritization of GI development, a critical component of sustainable urban water management in semi-arid regions.

Conclusion

This study developed a GIS-based, physically grounded framework to identify areas with the highest need for green infrastructure (GI) development, based on runoff generation potential and integrated social, environmental, and economic criteria. The approach combined the Rational Method for runoff estimation with publicly available spatial data and Multi-Criteria Evaluation (MCE) to produce a city-scale GI demand map. The spatial prioritization results revealed that a substantial portion of Tehran's Region 5—approximately 38%—has a very high need for GI implementation, primarily concentrated in the east and southeast. The proposed prioritization model offers several advantages. It incorporates a comprehensive set of criteria, applies a systematic GIS-based allocation method suited to semi-arid urban environments, and supports flood mitigation through scientifically validated runoff analysis. Additionally, the resulting GI demand map facilitates a clear understanding of complex, multi-layered urban planning challenges by revealing the relationships between runoff sources, flood-prone areas, and regions with high socio-economic and environmental demand.

This framework is a practical decision-support tool for enhancing urban sustainability by identifying priority zones for GI interventions. It offers a scalable approach that can support broader sustainable development goals within urban settings. Despite its contributions, this study has certain limitations. The absence of data on groundwater levels, property prices, and air pollution restricted the scope of analysis. Future research should aim to incorporate these datasets to refine the model and better capture the multi-dimensional impacts of GI. For example, integrating groundwater information could improve the understanding of water dynamics, property value maps could shed light on economic implications, and air quality data could strengthen assessments of GI's environmental benefits. Addressing these elements would further enhance the framework's utility in planning effective, resilient green infrastructure in semi-arid urban areas.

Declarations

Ethical Approval: Not applicable

Competing Interests: The authors declare no competing interests.

Author Contributions

Iman Saeedi: Conceptualization (equal), data curation (lead), formal analysis (lead), methodology (equal), investigation (equal), visualization (lead), writing original draft (lead). **Ali Reza Mikaeili -T:** supervision (lead), conceptualization (equal), investigation (equal), Methodology (equal), writing review and editing (equal), project administration (equal). **Abdolreza Bahremand:** project administration (equal), supervision (equal), methodology (equal), conceptualization (equal), writing review and editing (equal). **Abdolrassoul Salmanmahiny**: project administration (equal), supervision (equal), methodology (equal), conceptualization (equal), writing review and editing (equal).

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Data Availability

The datasets generated during and or analyzed during the current study are available from the corresponding author on reasonable request.

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